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Climate change and safe design of ship structures

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ABSTRACT

The paper addresses projected changes of wave climate in the North Atlantic and their impact on the safe design of ships, with a particular focus given on associated uncertainties. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) uses four scenarios for future greenhouse gas concentrations in the atmosphere called Representative Concentration Pathways (RCP). Two of these scenarios are applied to investigate how sensitive the future North Atlantic wave climate is to the emissions they represent. Winds obtained from six global climate models have been used to simulate waves for a historical period at the end of last century and to project waves for a future period towards the end of this century for these two scenarios. Based on these projections, possible changes in extreme wind and waves are investigated and the associated uncertainties are discussed. The occurrence of rogue-prone sea states which may trigger generation of rogue waves in the past and future climate is also studied. It is shown how the scientific findings on uncertainties related to climate change projections and rogue waves can be incorporated in the risk-based approach used in current design practice of tankers, and ship structures in general. The potential effect of climate change on the safety level of current design practice for tankers is demonstrated. Finally, the paper discusses how structural design of ships can be upgraded to account for climate change and rogue waves without necessarily leading to significant economic consequences.

1. Introduction

Marine safety is one of the main concerns of the shipping and offshore industry in general and Classification Societies in particular. The importance of including the state-of-the-art knowledge about meteorological (temperature, precipitation, wind) and oceanographic (waves, current) conditions in ship and offshore standards has been discussed increasingly by industry and academia in the last decades in several international forums, e.g. International Ship and Offshore Structures Congress (ISSC, 2009, 2012, 2015), ISSC-ITTC (International Towing Tank Conference) Workshops (Bitner-Gregersen et al., 2014; Kim, 2016).

Global warming and extreme weather events reported in the last years have attracted a lot of attention not only in academia (e.g. Wang and Swail 2006a,b; Hemer et al., 2010, 2013; Wang et al., 2015) and media but also in the shipping as well as offshore and renewable energy industry (e.g. ISSC, 2015; Bitner-Gregersen et al. 2013a,b; 2015; Hagen et al., 2013). A central question for the marine industries is: to what degree will climate change affect future ship traffic and design of ships as well as offshore and renewable energy structures?

The observed climate changes include natural variability of climate and anthropogenic climate change. Natural climate variability is due to the Earth's system dynamics, short term externally forced climate changes (volcanic activity, short term changes in solar radiation) and long term external forcing such as tectonic movement, solar radiation, changes in the Earth's orbit and asteroid bombardment. It has always been present. Anthropogenic climate change is due to human activities and is mostly associated with emissions of greenhouse gases to the atmosphere from burning of fossil fuels, but other factors such as land usage changes and deforestation also play a role. It leads to warming of the Earth's surface (IPCC, 2007; 2013). These two types of climate variations, natural and anthropogenic, interact with each other. Anthropogenic climate change brings trends in the mean value of metocean parameters, which can be neglected when talking about natural variability of climate in a more limited period of time, not covering

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thousands or millions of years. It may be also leading to changes of extremes as well as shapes of distributions of metocean parameters.

By now, a consensus has been reached within the scientific community that human activities contribute significantly to the observed warming of the Earth's surface resulting in changes of climate (IPCC, 2007, 2013). This also leads to changes in metocean conditions. Notice that natural variability of climate has been taken into account when relevant return values are calculated for use in design by considering sufficiently long meteorological and oceanographic (metocean) data records.

The Fifth Assessment Report (AR5), which was issued by the Intergovernmental Panel on Climate Change (IPCC, 2013), uses four scenarios for future greenhouse gas concentrations in the atmosphere called Representative Concentration Pathways (RCP) with radiative forcing of 2.6, 4.5, 6.0 and 8.5 W/m^2 by the end of the 21st century referred to as RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5, respectively. It summarises the latest scientific findings regarding climate change. A significant development has taken place since the issue of the Fourth Assessment Report (AR4) (IPCC, 2007), particularly in the increased use of quantitative statistical measures simplifying synthesis and visualization of climate model performance (see e.g. Sahany et al., 2012). However, similarly as in AR4, also in AR5 temperature, sea water level, precipitation, and ice extent received more attention compared to wind and waves. AR5 confirms the conclusions of AR4, that there are large regional variations in observed and projected climate-driven changes in metocean conditions.

Changes in wave and wind climate are expected to have the largest impact on marine structure design in comparison with other environmental phenomena since for most of marine structures wave induced loads are dominating. Changes in sea level combined with storm surge have little potential to affect ship design directly but may impact offshore and coastal installations. On the opportunity side, retreating arctic sea ice may open new areas for commercial ship traffic, but this is associated with additional risks related to operations in remote and harsh environments.

Climate change in terms of increased storm activity (intensity, duration and fetch) in some ocean areas, and changes of storm tracks, may lead to secondary effects such as increased frequency of occurrence of extreme wave events (abnormal waves also called rogue or freak waves), see e.g. Toffoli et al. (2011), Bitner-Gregersen and Toffoli (2014, 2015), Bitner-Gregersen (2016).

At present climate change and rogue waves are not explicitly included in Classification Societies' rules and Offshore Standards due to lack of sufficient knowledge about uncertainties associated with climate change projections and no full consensus about the probability of occurrence of rogue waves.

Although large uncertainties are associated with climate change projections, adaptation processes to climate change have already started in the marine industry to support safe design as at present in some ocean regions changes of metocean conditions cannot be excluded. In the Norwegian Standard NORSOK (2017), it is recommended to increase extreme significant wave height and wind speed by 4% on q-probability values due to climate change. Further, it is worth to mention that some changes in industry standards have also been introduced to account for rogue waves. The oil company STATOIL (see ISSC, 2013) has already introduced an internal requirement accounting in a simplified way for rogue waves when designing the height of a platform deck. This requirement is now implemented in the revised version of NORSOK (2017). Also, some revisions of the DNV GL rules for design of superstructures of passenger ships that account for rogue waves have also taken place as a result of the EC EXTREME SEAS (2013) project coordinated by legacy DNV (see e.g. EXTREME SEAS, 2013; Bitner-Gregersen et al., 2015).

A decision about possible systematic updates of Classification Societies' rules and standards for ships and other marine structures should be based on the state-of-art knowledge about climate change projections. The marine industry needs to know what changes in metocean conditions can be expected due to climate change in different parts of the ocean, what potential consequences they may have on design and safety of marine operations, and what methods can be used to account for these changes. Further, to be able to provide design and operational criteria accounting for climate change, relevant uncertainties associated with climate change projections need to be identified and quantified. This is of particular importance as uncertainties associated with climate change projections are currently large.

It may be argued that the potential effects of climate change on ship design can partly be compensated for by adjusting ship routes based on improved weather forecasts and with the support of advanced routing systems. However, weather forecasts are affected today by uncertainties and may not ensure avoidance of every storm, and not all types of ships are routing to the same degree. Further, the technology for deriving wave heights from marine radars has not yet fully been demonstrated in a satisfactory approach and is still under investigations. Finally, some ocean areas where an increase of significant wave height can take place may be difficult to avoid, e.g. for ferries, supply ships and FPSOs. Notice that a discussion of whether ship routing can be accounted for in current design practice is outside the scope of the present study.

The need to address climate changes in guiding documents became increasingly evident for DNV GL and was a motivation for initiation in 2013 investigations, summarized in the present paper, which were partly funded by Research Council of Norway (Bitner-Gregersen et al., 2013a). One of the main objectives was getting better insight into climate changes of wave conditions in the North Atlantic, as well as the associated uncertainties. Notice, that the North Atlantic wave climate is used today as a basis for ship design (IACS, 2001). To the authors knowledge the first time not only impact of climate changes on the significant wave height but also on the spectral wave period, associated wave steepness and wave spectra were investigated. Further, apart from the effects of climate change on total sea, the effects on wind sea and swell were also studied separately.

Although the present study concentrated on ships when investigating impact of climate change on loads and safety level of current design, the results addressing wind and wave are applicable also to offshore and renewable energy structures.

The paper is organised as follows. Section 2 is dedicated to identifying types of uncertainties associated with wind and wave projections; Section 3 shows projected changes of wind and wave climate in the North Atlantic and discusses associated uncertainties of these projections. Occurrence of rogue waves in the future climate is addressed in Section 4, while impact of climate change on design is discussed in Section 5. The paper closes with recommendations for future research needs and conclusions.

2. Type of uncertainties associated with climate projections

Climate models do not include any direct information about ocean waves, and dynamical or statistical downscaling must be employed to obtain information about waves from the climate model results. One possible approach is to use surface winds from climate models as input to numerical spectral wave models, e.g. WAM, WAVEWATCH III or SWAN, routinely used in operational wave forecasting by meteorological offices throughout the world. An alternative approach is to employ empirical relationships between the significant wave height and the mean sea level pressure through a statistical downscaling approach, see e.g. Wang et al. (2006b, 2012, 2014). Such an approach is naturally much less computationally demanding than the dynamic wave modelling approach, but also gives a more limited information about the properties of the wave field.

The dynamical approach has been adopted for the present study and uncertainties associated with its application for projections of climate changes of wind and wave characteristics are discussed below in the perspective of the definitions of uncertainties given in Appendix A.

Projections of future wind and wave climate include several steps

shown schematically in Fig. 1. Different uncertainties are associated with these steps. They will all impact projected wind and wave conditions, but in a varying degree, and consequently will affect design and operations of marine structures.

Projected wave data will be affected by uncertainties associated with a choice of the IPCC emission scenario, assumptions adopted by a Global Climate Model (GCM), a Regional Climate Model (RCM) and a wave spectral model (phase-averaged wave model).

The length of a data time series will define the statistical uncertainty (sampling variability), which will particularly affect evaluation of extreme values. The extremes will also be affected by an adopted extreme value analysis and a technique applied for deriving distribution parameters (model uncertainty). Further, a length of a data time series as well as the number of model runs will decide to which degree natural variability is accounted for.

3. Projected changes of wind and waves in the North Atlantic

3.1. Frame of the analysis

Several investigations carried out in the last decades have shown that there has been a statistically significant increase in the mean and extremes of significant wave height in several ocean regions over the last half of the 20th century, e.g. Neu (1984), Bouws et al. (1996), Gulev and Hasse (1998), Günther et al. (1998), Sterl et al. (1998), WASA Group (1998), Gulev and Grigorieva (2004), Caires et al. (2006),Wang and Swail (2006a, 2006b), Wang et al. (2012, 2014), Young et al. (2011), Dobrynin et al. (2012), IPCC (2007, 2013). For a review of the existing findings see also IPCC (2013), Bitner-Gregersen et al. (2013b). The observed increase of H_s has shown to be very regional dependent. An overall negative trend has also been observed in some ocean areas; see e.g. Dobrynin et al. (2012), Wang et al. (2012, 2014). These results have been shown to be region and climate model dependent. Much less attention has been given to wave period and wave spectra being also of importance for design of ships and other marine structures.

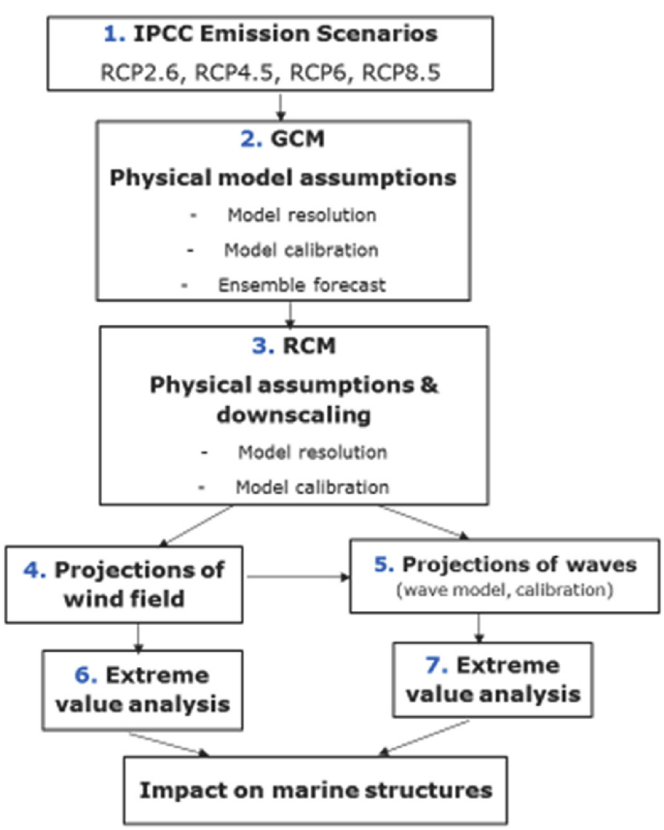

Fig. 1. Flowchart illustrating different steps of projections of wind and wave conditions.

In the present investigations two IPCC emission scenarios RCP 4.5 and RCP 8.5 have been analyzed and the sensitivity of the future North Atlantic wind and wave climate to these scenarios has been investigated. The choice of climate models is generally difficult due to the many models and experiments that are available, and the limited budget of the study has not allowed to run all models. The selection of CMIP5 models have been based on criteria that included the following:

- Number of ensemble members
- No or few restrictions on use
- The resolution in time and space
- Validation/evaluation/performance, including sea ice.

The selected CMIP5 models (see Table 1) provided near-surface winds (3-hourly) and sea ice concentration (updated monthly) for the wave spectral model simulations. Updated monthly ice cover was kept constant over the month. The third-generation wave model WAM (Hasselmann et al., 1988; Komen et al., 1994) forced by winds and with ice coverage obtained from six global climate models (GFDL-CM3, EC-Earth, HADGEM2, IPS-CM5A-MR, MRI-GCGCM3 and MIROC5), were used to project waves for a historical period and a future period. The grid resolution of the wave model is 50 km × 50 km and the data are sampled every 3rd hour (see Reistad et al., 2011). The WAM50 data are obtained by a simplified version of dynamical downscaling, as the wind field from the climate models is interpolated to the 50 km grid, and not by creating the 50 km winds by driving a finer scale atmospheric model with input from the global climate models. How the adopted approach affects the results in comparison with the latter one has not been investigated. The spatial resolution of the wind output varies between climate models and some models have multiple runs (ensemble members). An overview of the various climate model outputs that have been used in this study is given in Table 1. The resulting future wave climate is studied in detail by Aarnes et al. (2017).

It is implicitly assumed that the wind and wave climate is approximately stationary within each of the 30-year time periods analyzed herein, which has proved to be a reasonable assumption (Vanem, 2016a).

3.2. Uncertainties of projected mean and extreme values

3.2.1. Marginal distributions

The study has shown that the applied emission scenarios, the selected climate models and their ensemble members give rather different results, and the variations in the projections are significant. This makes it difficult to draw firm conclusions regarding the future wind and wave climate in the North Atlantic. However, some general observations can be drawn.

Fig. 2 shows the multi-model-multi-run average of mean significant wave height for the historical period as well as the projected changes assuming RCP 4.5 and RCP 8.5, respectively. These figures indicate that there might be a decrease of the mean H_s in large parts of the North Atlantic Ocean, with perhaps a slight increase in Arctic regions due to receding ice cover. The range of changes for the multi-model average mean H_s over the region is from a decrease of 22 cm to an increase of

Table 1
The CMIP5 global climate models used to force the wave simulations.

Model	Res	Historical		RCP 4.5/8.5	
		Period	#	Period	#
EC-EARTH	1.125° × 1.125°	1971–2000	3	2071–2100	3
HADGEM2-ES	1.875° × 1.25°	1970–1999	1	2081–2099	1
IPSL-CM5A-MIR	2.5° × 2.5°	1971–1999	3	2071–2099	1
MRI-CGCM3	1.125° × 1.125°	1971–2000	2	2071–2100	1
GFDL-CM3	2.5° × 2.0°	1970–1999	1	2071–2100	1
MIROC5	1.4° × 1.4°	1971–1999	5	2070–2099	3

61 cm (RCP 4.5) and a decrease of 33 cm to an increase of 75 cm (RCP 8.5).

However, the figures show the average over all runs, and results vary considerably across model runs. For example, Fig. 3 shows the projected changes in mean H_s from three different ensemble members from the same climate model, the EC-EARTH, for scenario RCP 4.5. The maximum historical (border 1) and future (border 2) ice cover is also plotted in the figure as well as the locations with the maximum positive/negative changes marked by the triangles. It is observed that there are notable differences, for example along the northern Norwegian coast; one of the runs suggests a slight increase in this area, one indicates a slight decrease and one indicates no significant differences. Notwithstanding these differences, most models suggest a general tendency towards lower mean H_s in a future climate over most of the North Atlantic Ocean. These changes in mean H_s are highly correlated with projected changes in mean wind speed, as shown in Fig. 4 (for the same model runs as the plots for mean H_s). Typically, the correlation between wind speed and significant wave height is in the order of 0.7–0.8 with higher correlations in enclosed seas (restricted waters). The maximum historical (border 1) and future (border 2) ice cover is also plotted in the figure.

For design and operational purposes changes in long-term joint distributions of metocean parameters and extreme values are of most importance. Return periods of interest may vary from 1-year to 100-years. It should be noticed that there may be significant differences in extremes derived directly from data and those calculated from the fitted distributions, as also shown by Bitner-Gregersen (2016), Aarnes et al. (2017).

In Fig. 5, the spatial pattern of annual historical maximum H_s obtained from the data is shown together with projected changes for the RCP 4.5 and RCP 8.5 future scenarios, respectively (from one of the EC-EARTH runs). The maximum historical (border 1) and future (border 2) ice cover is also plotted in the figure. Now, a much more variable tendency is seen, with some ocean regions experiencing an expected increase in extreme H_s. However, it should be noted that in most locations, the expected increases or decreases in the extremes are not statistically significant at the significance levels 5% and 1%, according to a standard Z-test for the difference between population means.

Obviously, estimates of return values corresponding to very large return periods are more uncertain since they depend on extrapolation beyond the support of the data, and there would be larger variability in higher quantiles depending on the adopted distributions and procedures for evaluating distribution parameters. The global model (all data), the Peak-Over-Threshold approach and the annual maxima model were used in the analysis as well as different fitting techniques (maximum likelihood, least squared, method of moments). As expected the differences in calculated extremes may be up to a few meters as highlighted by Vanem et al. (2015), Vanem (2015), Bitner-Gregersen (2016) and Aarnes et al. (2017). One consequence of such large uncertainties for high quantiles is that it will be very difficult to find statistically significant changes in extremes.

The plots presented in this paper are mostly included for illustrative purposes, and it is re-emphasized that the various models, different ensemble members and different emission scenarios yield variable results. For example, the spatial maximum mean significant wave height for the historical period ranges from 2.8 to 4.3 m across the various model runs. With regards to the estimated differences in the mean values between the historical and future runs, most models predict a predominantly decreasing trend of less than 1 m. For the higher quantiles, the differences between model runs are larger and there are much more variable differences in the extremes between historical and future runs. However, due to the large uncertainties these differences are mostly not statistically significant, although some exceptions are found with significantly decreasing or increasing trends at different locations for certain wave model runs. For an overview of all the individual simulations developed by MET Norway, reference is made to Aarnes et al. (2017).

As an example, an increase of the 20-year extreme H_s from 0.2 m up to ca. 2.0 m can be expected in the future period compared to the historical period when the wave model is forced by the GFDL-CM3 or EC-EARTH winds. This increase is slightly higher when the 100-year extreme, H_s is considered (Bitner-Gregersen, 2016). Further, differences between H_s extremes calculated for the three EC-EARTH ensemble members are in some cases larger than differences between projections given by the GFDL-CM3 and EC- EARTH models. This indicates that natural variability, represented by ensemble members, may dominate climate change projections making evaluation of the effect of anthropogenic climate changes even more difficult. Again, these changes are highly regional- and model-dependent (see also Wang et al., 2015).

3.2.2. Joint distributions

For marine design applications, the joint distribution of significant wave height and peak/zero-crossing wave period is of importance as not only wave height but also wave period will impact loads and responses of marine structures. Notice, that long-term metocean description will not be affected significantly by sampling variability (statistical uncertainty due to limited number of data) but a choice of distributions used to fit the wave data and a fitting technique applied will affect the results.

There exist several approaches for establishing joint distributions of metocean variables (see e.g. Bitner-Gregersen, 2012). Often the Conditional Modelling Approach (CMA) proposed by Bitner-Gregersen and Haver (1991) is used. CMA utilizes the complete probabilistic information obtained from simultaneous observations/numerical data of

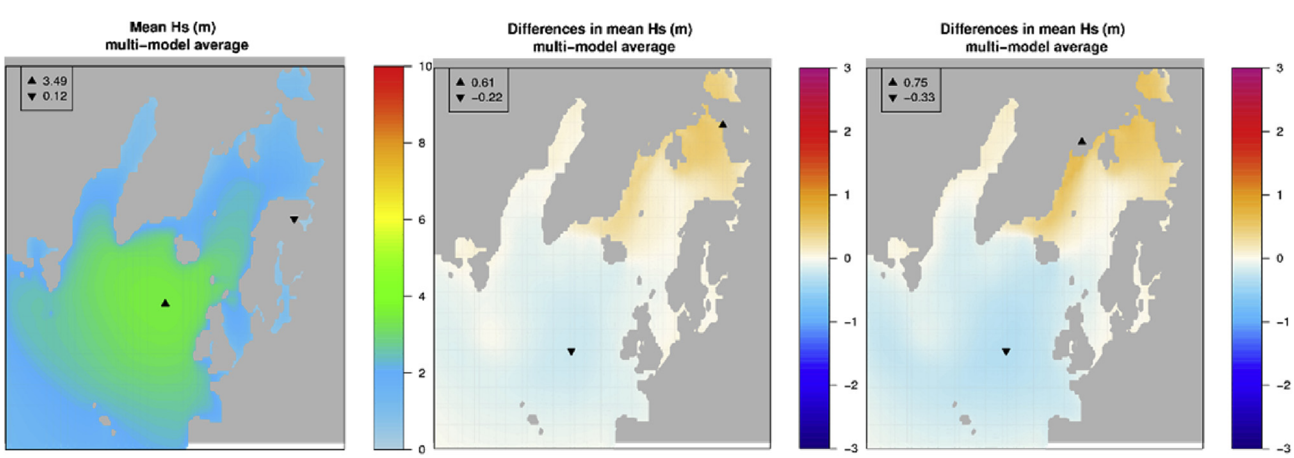

Fig. 2. Average mean H_s over all models and all runs for the historic period (left) and average projected differences in mean H_s for RCP 4.5 (center) and RCP 8.5 (right) scenarios, respectively. The locations with the maximum positive/negative changes are marked by the triangles ▲and ▼, respectively.

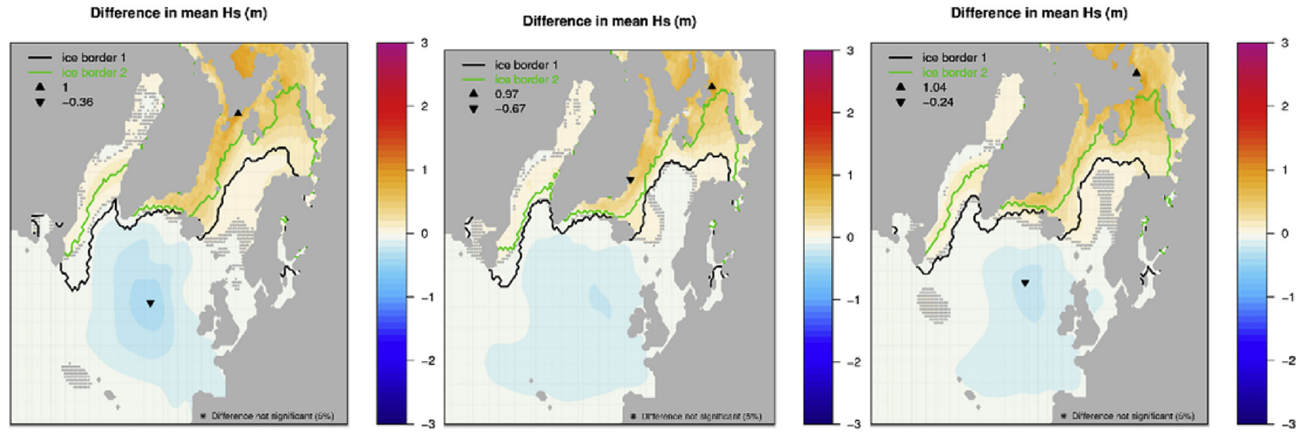

Fig. 3. Projected changes in mean H_s for three different model runs from the EC-EARTH model. The locations with the maximum positive/negative changes are marked by the triangles ▲ and ▼, respectively. Maximum historical (ice border 1) and future (border 2) ice cover.

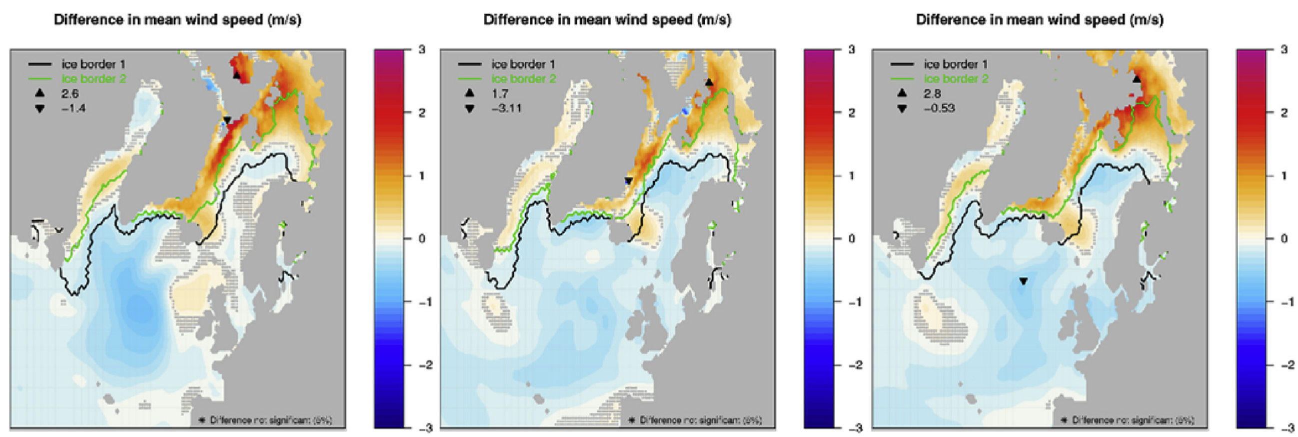

Fig. 4. Projected changes in mean wind speed for three different model runs from the EC-EARTH model. The locations with the maximum positive/negative changes are marked by the triangles ▲and ▼, respectively. Maximum historical (ice border 1) and fiture (border 2) ice cover.

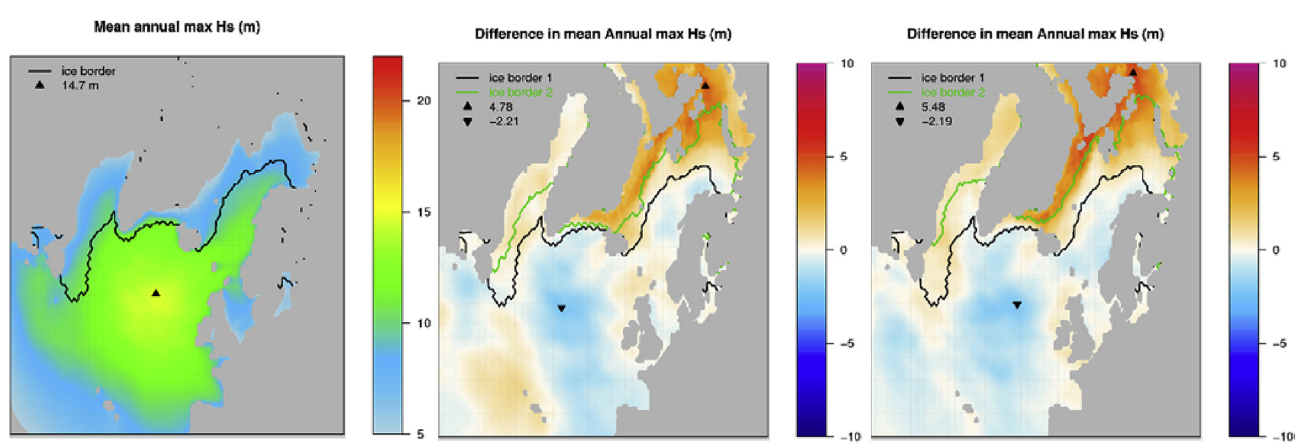

Fig. 5. Annual max H_s for historical period (left) and projected changes in RCP 4.5 (center) and RCP 8.5 (right) from an EC-EARTH model run. The locations with the maximum positive/negative changes are marked by the triangles ▲and ▼, respectively. Maximum historical (ice border 1) and future (border 2) ice cover.

metocean variables. It is based on the Rosenblatt Transformation (see Madsen et al., 1986), where the joint density function is defined by a marginal distribution and series of conditional density functions. Each of these functions is modelled using parametric functions that are fitted to the conditioned data by some form of estimation process.

Recently, much attention has been given to the use of multivariate copulas in establishing joint probability models (for review see e.g. ISSC, 2015). Copula models are based on the marginal distributions of the considered variables and the dependency between them what allows easily to model and estimate the distribution of random vectors by estimating marginal distributions and copulas separately. There are various ways to model a copula which describes the dependence structure between the variables. A comparison of various parametric copulas is given in Vanem (2016a). The study revealed that straightforward application of

any of the standard parametric families of copulas fails to give good joint models for the wave climate data. However, it was emphasized that for example a conditional model can be expressed within the copula framework, so the very same model can, in principle be established equally by a conditional modelling approach and the copula approach.

Different joint distributions were applied to the WAM50 wave data for a particular location (Vanem, 2016b; Bitner-Gregersen, 2016), and the effect of climate change on the joint description was investigated. Results from this one location and model runs have indicated that the relation between significant wave height and wave period might change in the future scenarios, most notably in the extremes. Fig. 6 shows the fitted joint distribution of H_s and T_p for a historic and a future run of the EC-EARTH model using the RCP 4.5 scenario for location 6 (see Fig. 7). This figure suggests that joint distributions may become narrower in a future climate and in some ocean regions the conditional standard deviation of wave period given H_s may be reduced compared to the historical data.

Often, environmental contours (see DNV, 2014) are used in marine structures' design to derive extreme wave conditions. Hence, it could be of interest to compare estimated contours based on historical wave data and projected future wave data. Such comparison is shown in Fig. 8, where wave data for location 6 from the GFDL-CM3 model have been used to construct environmental contours for the 25-year extreme sea states for the historical period, and the RCP 4.5 and RCP 8.5 scenarios, respectively. These environmental contours are notably different for the future scenarios, indicating that ship design might be affected by climatic changes but still more investigations are needed before firm conclusions can be reached. The alternative approach for establishing environmental contours proposed by Huseby et al. (2013, 2015) was also investigated in the project and compared by Vanem and Bitner-Gregersen (2015) with the commonly used IFORM contours due to Winterstein et al. (1993) documenting limitations of the methods.

Intuitively, one would expect that the emission scenario RCP 8.5 should affect the extreme wind and wave values more than the scenario RCP 4.5, however, the investigations carried out have shown that this might not always be the case. This will depend on wind and wave characteristics analyzed, and return periods and locations considered. Further, deviation between predictions of wind and wave extremes for the RCP 4.5 and RCP 8.5 scenario will be a function of return period, as illustrated in Fig. 9 for the GFDL-CM3 model run for the location 6.

It is interesting to notice also that in some ocean regions the number of severe winds is increased in the future period. Further, there are some

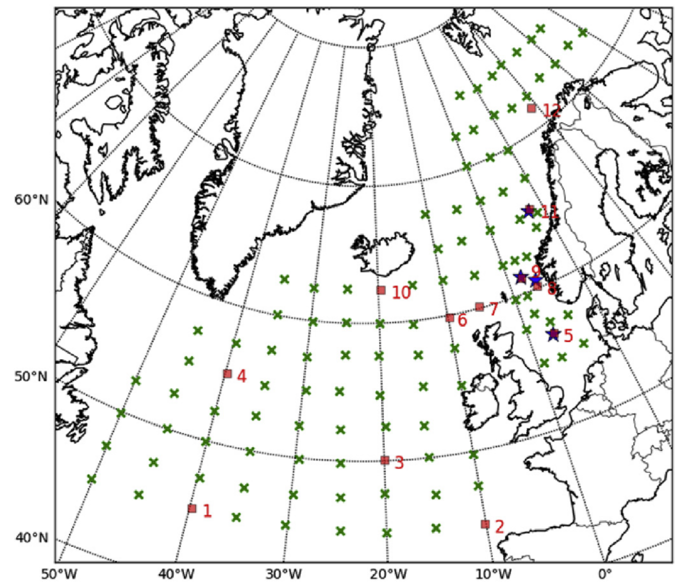

Fig. 7. Map showing position for which wave spectra are available (green crosses). The numbered locations indicated by red squares show the 12 points selected for further analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

severe storms in the future climate with wind speeds considerably higher than the largest wind speed reported in the historical period. This may partly explain an increase of extreme significant wave heights in the future climate in some areas of the North Atlantic.

Fig. 10 shows an example of the joint distribution of significant wave height (total sea) and wind speed (H_s, U_w) (for model description see Bitner-Gregersen and Haver, 1991) for the GFDL-CM3 model, for historical period and the scenario R 4.5. As seen in the figure the shape of the (H_s, U_w) distribution is changed in the future climate. It is interesting to notice that in the considered location over the period 2071–2100 wind speeds of 2–3 m/s higher than the largest wind speed reported in the period 1971–2000 are observed.

In some locations, an increase of significant wave height in the future climate may be partly caused by presence of combined seas and an increase of significant wave height for swell. Also, changes of the shape of the (H_s, T_p) distributions of wind sea and swell have been observed

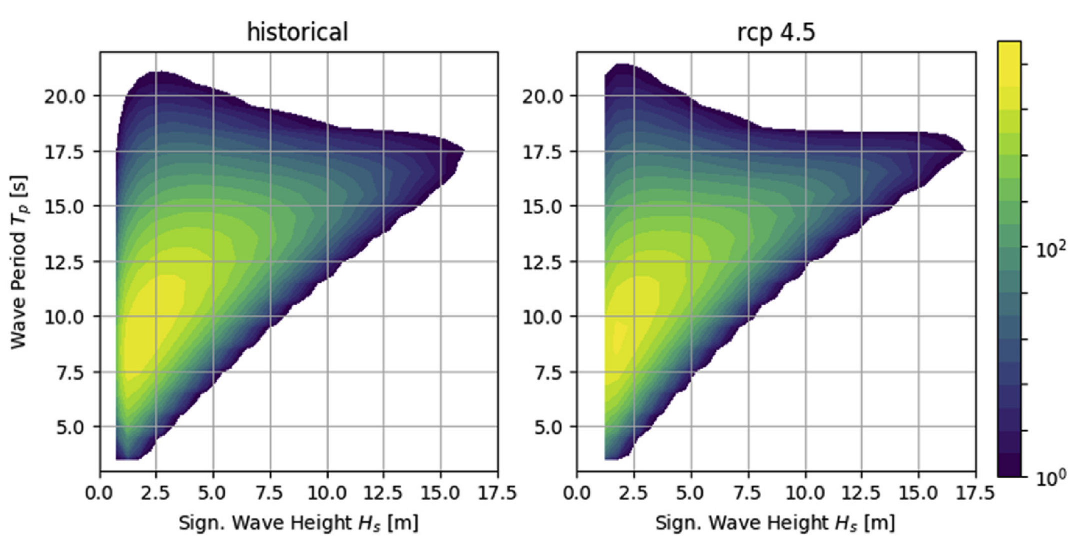

Fig. 6. Joint (H_s, T_p) distribution fitted to the WAM50 data from the period 1971–2000 (left) and 2071–2100 (right), the North Atlantic location 6, total sea, the EC-EARTH model, ensemble member 12. The contours' colours represent the number of observations in the 30-year period. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

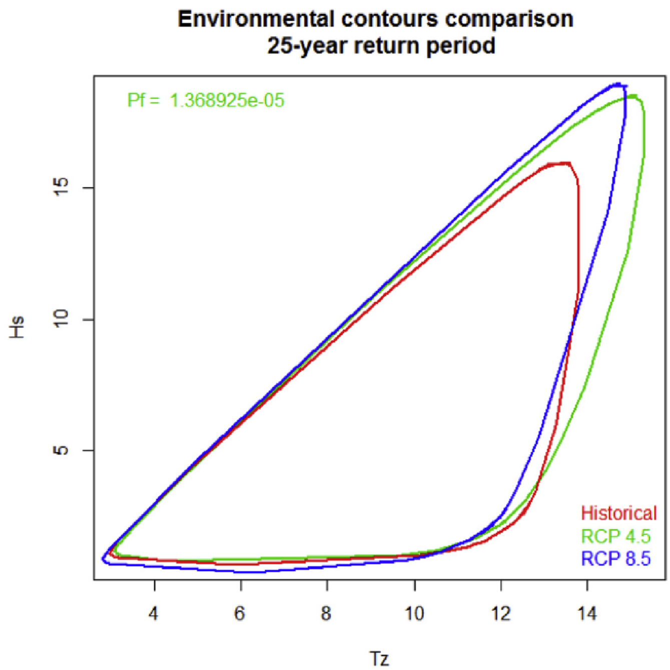

Fig. 8. Changes in 25-year environmental contours in a changing climate, GFDL-3CM model, location 6.

(Bitner-Gregersen, 2016) in the future scenarios.

4. Occurrence of rogue waves in the future climate

The occurrence of rogue waves, their mechanisms and detailed dynamic properties are through recent years' research efforts now becoming clearer, and consistency between numerical models and experimental data has been documented by several studies. Several different mechanisms may be responsible for generating these waves such as linear focusing (frequency or angular, see e.g. Donelan and Magnusson, 2017), wave–current interactions, crossing seas, quasi-resonant nonlinear interactions (modulational instability), shallow water effects and wind (For a review of different mechanisms see Onorato et al., 2013; Bitner-Gregersen and Gramstad, 2016). Although climate change and rogue waves represent two different phenomena, the ongoing investigations on rogue waves poses an important question for the shipping and marine industries in general: Will we see more of these waves in a changing climate? This may happen due to increase in storm activity (intensity, duration and fetch) in some regions, and changes of storm tracks leading to changes of occurrence of crossing seas.

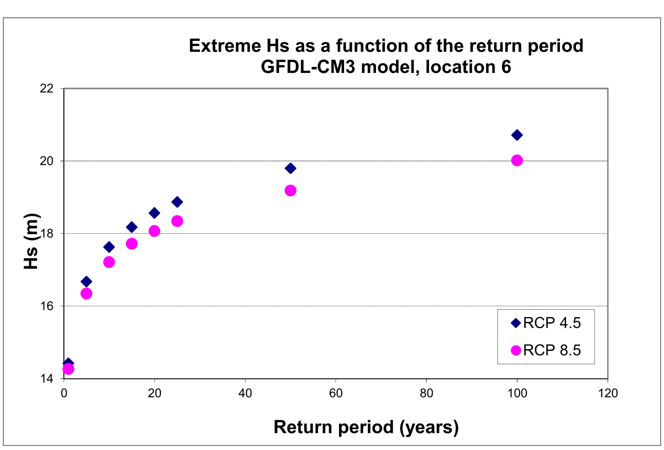

Fig. 9. Extreme H_s as a function of the return period, the GFDL-CM3 model, location 6.

It has been shown that the occurrence of modulational instability in deep water is characterized by high wave steepness and a narrow wave spectrum, both in frequency and direction, and can be identified by the Benjamin-Feir Index (BFI), see e.g. Onorato et al. (2006, 2013). The BFI is a measure of the relative importance of nonlinearity and dispersion. It can be defined as BFI$=(k_pH_s/2)/(\Delta\omega/\omega_p)$, where $\Delta\omega/\omega_p$ is the frequency spectral bandwidth ($\Delta\omega$ is often measured as the half-width at half-maximum of the spectrum and ω_p is the spectral peak frequency). Provided the wave field is sufficiently steep and narrow banded in frequency and direction, rogue waves are expected to be generated when BFI=O(1). However, as mentioned the occurrence of a steep sea state is not alone sufficient to trigger modulational instability. In addition, the wave spectrum needs to be narrow-banded in frequency and direction when one wave system is present.

Interestingly enough, however, Onorato et al. (2006, 2010) have shown using Nonlinear Schrödringer (NLS) equations that the modulational instability and rogue waves can be triggered by a peculiar form of directional sea state, where two identical, crossing, narrow-banded random wave systems interact with each other. Such results have been supported by recent numerical simulations of the Euler equations by HOSM (Higher Order Spectral Method) and experimental work carried out at the MARINTEK Laboratories (Toffoli et al., 2011). They indicated a dependence of the angle between the mean directions of propagation of the two crossing wave systems, with a maximum rogue wave probability for angles of approximately 40°.

Later, the study of Bitner-Gregersen and Toffoli (2014) showed using hindcast data that occurrence of rogue-prone crossing sea states with approximately the same significant wave height and mean frequency is location specific, depending strongly on local features of wave climate. These seas have been observed in the North Atlantic as well as in the North and Norwegian Seas but only in low and intermediate sea states. Further, the numerical simulations carried out by HOSM have shown that although directionality influences the occurrence of extreme waves in crossing seas, rogue waves can occur not only for narrow-banded wave directional spreading but also when it is broader. It seems that the most critical condition for occurrence of rogue waves in crossing seas is associated with energy and frequency of two wave systems while the angle between the wave systems and directional spreading will decide how large extreme waves will grow. The 40° angle and narrow-banded directional spreading seem to be generating the largest waves. Such an unusual sea state of two almost identical wave systems (approximately the same significant wave height and mean frequency) with high steepness and different directions was observed during the accident to the cruise ship Louis Majesty (Cavaleri et al., 2012).

Occurrence of rogue waves due to modulational instability and crossing seas in the past and the future climate has been studied in by Bitner-Gregersen and Toffoli (2015), Bitner-Gregersen (2016) and Gramstad et al. (2017).

The reported increase of steep sea states in the future climate (Bitner-Gregersen and Toffoli, 2015) may increase occurrence of rogue waves. Further, using data from one location and the GFDL-MC3 climate model it was indicated that an increase of rogue-prone crossing seas could also be expected (Bitner-Gregersen, 2016). These investigations, more systematically, were continued by Gramstad et al. (2017).

In addition to providing various integrated wave parameters such as significant wave height H_s and wave periods T_p and T_z, the WAM50 runs used provided also the full directional wave spectrum at selected locations (indicated with green crosses in Fig. 7). From analysis of the full wave spectra we have been able to investigate the occurrence of sea states that are known to be related to higher probability of extreme and rogue waves, in the past and future wave climate. For this particular study 12 locations in the North-Atlantic were selected, as shown by red squares in Fig. 7. The results of these investigations are reported in Gramstad et al. (2017).

Based on the current knowledge on rogue waves summarized above, we have considered two types of rogue-prone sea states. Firstly, sea states

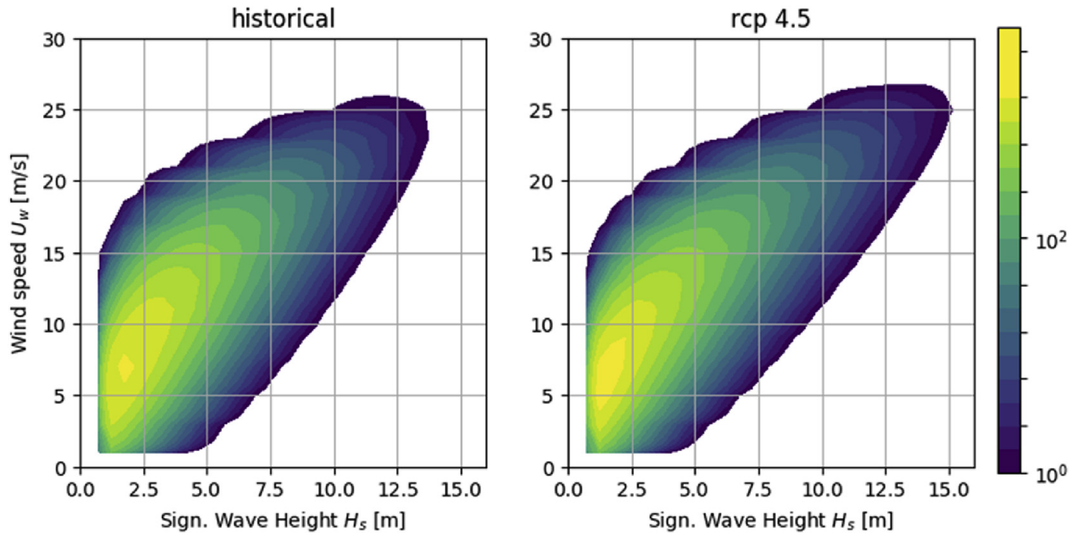

Fig. 10. Joint (H_s, U_w) distribution fitted to the WAM50 data from the period 1971–2000 (left) and 2071–2100 (right), the North Atlantic location 59.28°N, 11.36°W, total sea, the GFDL-CM3 model, RP4.5 scenario. The contours' colours represent the number of observations in the 30-year period. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

that have large BFI (BFI > 1) and narrow directional spreading σ < 30°. The second type of sea state we have considered is crossing seas where the two wave systems propagate with a crossing angle of 40°–60° and where the two systems have similar values for H_s and T_p.

It should first be noticed that such sea states are relatively rare in the WAM50 data, occurring in about 0.1–1% of all sea states, depending on location. It is also interesting to notice that while the sea states with large BFI and narrow directional spreading mainly occur in high sea states and are highly overrepresented among sea states with $H_s > 10$ m, the rogue-prone crossing sea states tend to occur in lower sea states with $H_s < 6$–8 m, confirming the earlier findings of Bitner-Gregersen and Toffoli (2014).

When looking at the occurrence of the rogue-prone sea states in the future climate compared to the historical period 1970–2000, the results of Gramstad et al. (2017) show that there are very large variations, both with respect to different locations and with respect to the different climate models. Fig. 11 shows the observed change in occurrence of rogue-prone crossing sea states (in percent) between historical period and future climate using the RCP 8.5 emission scenario for the twelve locations given in Fig. 7 and using the six different climate models. Empty cells indicate cases where no significant change is detected according to the chi-squared test for statistical difference between historical and future periods.

As indicated by Fig. 11 there seems to be large uncertainties related to the projections of these sea state properties. Nevertheless, in certain locations we do see some more clear results. For example in the northernmost location that we considered, outside the Norwegian coast of Finnmark (location 12 in Fig. 11), a significant increase in the range 110%–360% in the number of rogue-prone crossing seas is observed for all six climate models. This shows that in some ocean regions one may see a significant change in the number of sea states with higher probability of rogue waves, but that this is strongly location dependent, and that in general the uncertainties related to the climate projections for such parameters are still very large at present. It should be noticed that along the coast of Finnmark, the receding ice cover will obviously change the wave climate.

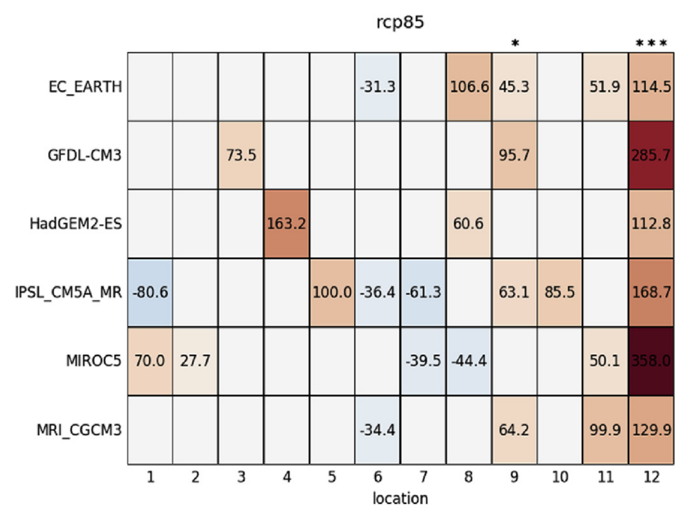

Fig. 11. The observed change in occurrence of rogue-prone crossing sea states (in percent) between historical period and future climate using the RCP8.5 scenario, in 12 different locations in the North-Atlantic for the six different climate models. Empty cells indicate cases where no significant change is detected.

5. Impact of climate change on design

The traditional format of Classification Societies Rules is mainly prescriptive, without a transparent link to an overall safety objective. The International Maritime Organization (IMO, 1997, 2001) has developed guidelines for use of the Formal Safety Assessment (FSA) methodology in rule development, which will provide risk based goal-oriented regulations that are well balanced with respect to acceptable risk levels and economic considerations. Formal Safety Assessment consists of five interlinked steps; (1) a hazard identification, (2) a risk analysis (3) identification of risk control options, (4) a cost benefit assessment of the risk control options, and (5) a recommendation to decision makers. Risk is defined in FSA as a product of probability of occurrence of a hazard multiplied by its consequence estimated usually as a monetary value (see e.g. Skjong and Bitner-Gregersen, 2002). FSA will be used when considering implementation of climatic changes and rogue waves in design practice. In this case an increase of H_s or occurrence of a rogue wave will represent a hazard.

When performing FSA for ship structures it is beneficial to apply Structural Reliability Analysis (SRA) in the risk assessment (step 2) and in the cost-benefit assessment (step 4). The reliability methods (see Madsen et al., 1986) allow quantifying in a probabilistic way the uncertainties in the different parameters that govern the structural integrity. This allows

reliability assessment of structural components or a structure. Further, reliability-based design of a structural component (or a structure) provides a means to satisfy target reliability with respect to specific modes of failure. The probabilistic approach can be used for calibration of partial safety factors in the development of LRFD (Load and Resistance Factor Design) codes, and for development of acceptance criteria for structural designs, confer DNV CN 30.6 (1992), ISO 2394 (1998), Bitner-Gregersen et al. (2002), Skjong and Bitner-Gregersen (2002) and Hørte et al. (2007a, 2007b). Standard software allowing carrying out structural reliability calculations is available within industry. Also, complicated nonlinear effects can be included by embedding a time domain simulation code in a reliability code, such as the PROBabilistic ANalysis code PROBAN® (DNV, 2012).

How to account for climate change trends and rogue waves in the risk approach based on the FSA methodology is schematically shown in Bitner-Gregersen et al. (2015). Rogue waves can be included directly in the metocean description (Alternative 1) or as a correction in a load distribution (Alternative 2).

When considering accounting for climate change and rogue waves on marine structure design a distinction will need to be made between existing structures and new ones. Maintaining the same safety level as current design will be crucial in this process. SRA is recommended to be used in evaluation of safety level of existing structures as well as future ones.

In light of the findings regarding potential changes of significant wave height summed up in the previous sections and the results of the EC EXTREME SEAS project, projected impacts that climate change and rogue waves may have on the design of tankers has been investigated in Bitner-Gregersen et al. (2015). Below an example of the applied methodology is given for illustration only.

It should be noticed that anthropogenic climate change has non-stationary character bringing trends in the mean value of metocean parameters which are not accounted for in current design practice of marine structures. The time variable is not included in design today and we have suggested how it may be done.

The IACS Common Structural Rules for Tankers, IACS (2010), has been used to demonstrate these effects on hull girder collapse of tankers. Five oil tankers, ranging from Product Tanker to VLCC (Very Large Crude Carrier) have been considered. Notice, that the ship length of the tankers is ranging from 174.5 m (Product Tanker) to 320 m (VLCC). An increase of the extreme significant wave height by 0.5 m, 1.0 m, 1.5 m and 2.0 m has been investigated, see Bitner-Gregersen et al. (2015) for details. These increases of H_s may represent any type of uncertainties, depending on an ocean location considered, adopted global and regional climate models, length of data series and statistical models and fitting techniques used in the extreme analysis.

The North Atlantic joint (H_s, T_z) model adopted by CSR for Tankers (IACS, 2010; IACS, 2001), with a 3-parameter Weibull distribution for H_s and a conditional lognormal distribution for the zero-crossing wave period T_z given H_s, has been modified to reflect the climate change. The H_s distribution has been shifted by a constant value corresponding to the specified increase of H_s. The formulation of the conditional distribution of T_z has been kept unchanged (Bitner-Gregersen et al., 2011, 2013b, 2015). This simplification is considered to be acceptable for extremes but not for fatigue calculations. Three cases have been considered: Case a) increasing extreme H_s by a constant value (Bitner-Gregersen et al., 2011), Case b) modifying the joint distribution using closed form expressions for the Weibull scale and location parameter (the shape parameter is kept constant) proposed by Vanem and Bitner-Gregersen (2012), Case c) assuming that the increased extreme significant wave height instead of being a fixed value (as in Case a) is normally distributed with COV = 0.25 (Bitner-Gregersen et al., 2015).

The above described approaches can be used when only historical wave data are available. Alternatively, if climate data exist, the joint (H_s, T_z) distribution could directly be fitted to climate data and applied in the reliability calculations; this has not been done in the present study due to large uncertainties associated with climate change projections. The proposed increase of significant wave height by 0.5 m up to 2.0 m is of more general applicability and can be applied to the state-of-the-art climate change findings today and in the future.

The three approaches for including effects of climate changes in the joint (H_s, T_z) distribution give approximately the same results (Bitner-Gregersen et al., 2015). Case b shows a slightly higher probability of failure for the largest increase of H_s compared to Cases a and c. The difference between Case a and Case c is negligible indicating that the increase of the most probable extreme H_s, reflecting systematic error, has much larger effect on current design practice than the random error associated with the extreme H_s prediction.

For illustration an example the annual probability of failure for the considered Aframax (length 263 m) as a function of the deck area (total cross sectional area of deck plate and stiffeners), when modification of (H_s, T_z) distribution according to Case c is applied, is shown in Fig. 12. The deck area equal 1 refers to the initial input design of the ship (Base Case) as used by CSR for Tankers (IACS, 2010).

The investigations have shown that an increase of the significant wave height beyond 0.5 m in the North Atlantic will have a large impact on the current design practice for tankers. The steel weight of the deck in the midship region may need to be increased to maintain the current safety level. Longer ships would require a larger increase in the ship deck area. If the significant wave height increases by 1.0 m, the deck area will need to be increased by 9% for the VLCC and by 5% for the Product Tanker. Increasing the hull girder strength in a more optimal way without increasing the steel weight, not addressed herein, could also be considered and is encouraged to do in the future. Use of high strength quality steel could also reduce necessity of large increase of the steel weight.

In this context it should be noticed that the results presented here are for "net scantlings", (without the corrosion addition) which is part of the explanation of, what some would say, relatively high failure probabilities. Gross scantling, which is the net scantling plus the corrosion addition, would reduce the failure probabilities by approximately an order of magnitude.

Similar trends as for H_s increase due to climate change have been found when the bending moment due to presence of rogue waves is increased (Bitner-Gregersen et al., 2015). A 10% increase of the bending moment would increase the cost of ship deck by approximately 10% in order to maintain the safety level. Rogue waves leading to increase of wave bending moment below 5% will not have significant impact on reliability level of current design practice of tankers. Further, as for climate change it might be possible to increase the hull girder strength in a more optimum way using less steel as demonstrated in the EC EXTREME SEAS project by the Portuguese ship yard ENVC for three vessels built recently by ENVC (Ro-Pax Ferry, Heavy-Lift Container and

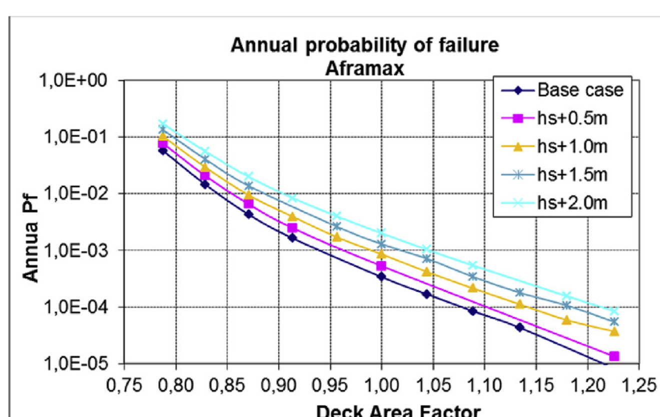

Fig. 12. Annual probability of failure, Aframax, the modified (H_s, T_z), Case c. *After* Bitner-Gregersen et al. (2015).

Asphalt Tank Carrier). It was shown that extra building costs related to accounting for rogue waves could be marginal or none, depending on how initial design and high strength steel quality is used. Similarly, the German ship yard Meyer Werft (MW) in collaboration with legacy GL Hamburg and the University of Duisburg -Essen has shown in EXTREME SEAS that redesign of a cruise ship superstructure to stand against rogue waves can be done when the total price for a cruise liner will increase slightly but the operational costs will remain unchanged.

6. Discussion and conclusions

In this paper, climatic changes in wind and wave conditions that are important for the safe design of ship and other marine structures have been addressed. These are mostly related to potential changes in various wave parameters. In order to assess the expected changes in these parameters, one needs to rely on climate simulations and projections from global climate model as well as numerical wave simulations from physical wave models. The global climate models provide historical and future wind fields that can be used to force the numerical wave models together with simulated ice coverage from the climate models.

We have demonstrated that there are large uncertainties associated with climate change projections of the North Atlantic wind and wave conditions at present. We see large variability between the different climate models and across different ensemble members of the same model as well as between the analyzed emission scenarios. The results are location dependent. These uncertainties will also affect predictions of occurrence of rogue waves. Therefore, firm conclusions regarding climate changes are difficult to reach today. However, the results indicate that the range of possible changes in the operational environment of ships is sufficiently large to influence the safety of marine operations and ship and marine structures' design in some ocean regions. Marine structures may experience higher environmental loads in some regions, especially where retreating sea ice cover has led to longer fetch (Aarnes et al., 2017; Thomson and Rogers, 2014). Therefore, to be on the safe side in design, an increase of extreme significant wave height and wind speed by 4% on q-probability values due to climate change proposed by NORSOK (2017) may be justified. We can expect that these numbers might be revised when new findings regarding climate changes are available in the future.

Compared to other climate variables such as temperature, precipitation and sea level rise, winds have a more tenuous link to emission scenarios (see e.g. de Winter et al., 2013). As pointed out by Zappa et al. (2013), extratropical cyclones grow as baroclinic instabilities, and changes to the baroclinicity of the atmosphere will thus affect cyclone tracks and intensity. Increasing moisture content can potentially lead to more explosive cyclones, but on the other side, polar amplification of global warming, weakening meridional overturning circulation and retreating sea ice can act to weaken North Atlantic storms in the future.

Also, the extent of sea ice coverage is highly uncertain, and for some of the climate models explored in this study, the ice coverage seems to be clearly inaccurate. The large variability in wind output, as well as the ice coverage, translates directly to the high uncertainty of simulated wave fields. It should be noticed that physical wave models are affected also by various uncertainties associated with models' assumptions and models' resolution that will impact results. The latter may give biased extremes and predictions of rogue waves.

Earlier, the climate community has put more emphasis on temperatures, sea level rise and precipitation, and less on the prediction of surface winds important for wave projections. There are currently initiatives to develop fully coupled atmosphere-wave-ocean climate models (Li et al., 2016, 2017) and combined with increased spatial resolution uncertainties associated with wave climate projections may be reduced in the future.

Secondary effects of climate change such as increased frequency of occurrence of rogue waves needs also to get attention. This will require further insight into potential changes of wave spectra. Recently met-offices have started to archive wave spectra from hindcast runs providing new opportunity for such studies. The marine industry would much welcome access to these data.

The marine industry has methods and various tools, although some may need to be enhanced, to deal with climate changes but systematic evaluation of their impact on loads and responses of different structure types is still lacking. Such studies are needed to quantify potential implications of climate change on design and marine operations as well as on related economic consequences. Further, they are necessary for specification of the existing margins in current design practice. Retaining the current safety level in rules and standards during this process is crucial. In addition, costs associated with possible accounting for climate change and rogue waves should be kept low through the introduction of innovative designs.

A decision regarding possible updates of Classification Societies' rules and standards for ships, and marine structures in general, should be based on the state-of-art knowledge about climate change projections. Therefore, the marine industry needs to closely follow developments on climate change and collaborate with the climate and wave community. The latter is essential in order to push state-of-the-art knowledge about climate changes relevant for design and the safety of marine operations. Establishment of expert panel(s), including external researchers and users, to discuss results and exchange information about climate changes is highly recommended. It should be mentioned that the shipping, and marine community in general, is interested not only in climate change projections but also in uncertainties associated with them.

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Appendix A. Definition of uncertainties

Different scientific and engineering groups use different definitions of uncertainties. Herein we adopt the definitions used by the structural reliability community which have been developed having Structural Reliability Analysis (SRA) in mind.

Classification of uncertainties for metocean description has been suggested by Bitner-Gregersen and Hagen (1990). The proposed definitions were later generalised and in 1992 included in DNV Rules (DNV, 1992). Generally, uncertainty related to an environmental description may be divided into two groups: aleatory (natural variability) uncertainty and epistemic (knowledge) uncertainty. Aleatory uncertainty (see e.g. DNV, 1992) represents a natural randomness of a quantity, also known as intrinsic or inherent uncertainty, e.g. the variability in wave height over time. Aleatory uncertainty cannot be reduced or eliminated.

Epistemic (knowledge) uncertainty represents errors which can be reduced by collecting more information about a considered quantity or by improving the measurement methods. In accordance with Bitner-Gregersen and Hagen (1990), this uncertainty may be classified into: data uncertainty, statistical uncertainty, model uncertainty and climatic uncertainty.

- Data uncertainty is due to imperfection of an instrument used to measure a quantity, and/or a model used for generating data. If a quantity is not obtained directly from the measurements but via some estimation process, e.g. significant wave height, then the measurement uncertainty must be combined with the estimation or model uncertainty by appropriate means.

- Statistical uncertainty, often referred to as estimation uncertainty is due to limited information such as a limited number of observations of a quantity (sampling variability).
- Model uncertainty is due to imperfections and idealisations made in physical process formulations as well as in choices of probability distribution types for representation of uncertainties and due to the estimation technique applied for calculation of the distribution parameters.
- Climatic uncertainty addresses the representativeness of measured or simulated wave history for the (future) time period and area for which design conditions need to be provided. A data set has to be sufficiently long to eliminate climatic uncertainty, e.g. to avoid biasing towards years characterized by severe winds or by calm weather only.

To characterise the accuracy of a quantity, e.g. significant wave height, H_s, it is necessary to distinguish between systematic error (bias) and precision (random error) with reference to the true value τ, which usually is unknown.

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